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ON THE BURNING VELOCITY OF ATOMIZED FUEL

V. Ya. Basevich

The burning of atomized liquid fuel attracts special attention, since it is one of the most widespread processes in engineering (gas turbines, diesel engines, various heating devices etc.).

At the present time a large number of papers on the diffusion burning velocity of fuel drops is known [1-8]. These investigations have led to the formulation of a basic law for the burning velocity of drops, a law which essentially reflects the vaporization of the drops under the action of the flame. This law is usually presented as a linear relationship between the square of the drop diameter D and the combustion time τ:

$$D_0^2 - D^2 = k\tau, \tag{1}$$

where D_0 and D are the initial and present drop diameters; and k is the so-called burning-velocity constant.

In the case of a number of hydrocarbons the experimental values obtained for the constant k are in general agreement. These values, which, as a rule, are obtained in model experiments, correspond to those idealized conditions under which the experiments were carried out: in the majority of cases this is a single large drop in stationary air or a model of a drop in the form of a porous body being blown in a

slow air stream, etc.

Such an idealization is necessary in order to establish the combustion law, as well as for an exact determination of $\underline{k}$, and is completely justified. However, an evaluation of the values of $\underline{k}$ under more complicated conditions is desirable, particularly for the burning of an ensemble of drops of different dimensions in a high velocity turbulent flow.

In the present paper, on the basis of a number of assumptions, an attempt has been made at such an evaluation. For comparison, the burning velocities of homogeneous mixtures have also been measured and compared.
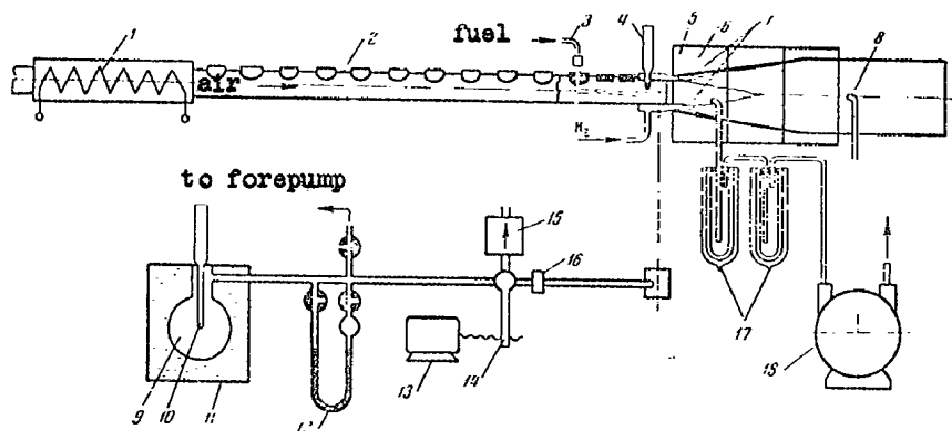
Fig. 1. Experimental apparatus

1) electrical preheater; 2) pipe; 3) jet; 4) thermometer;
5) turbulator; 6) combustion chamber; 7) burner; 8) gas
sampler; 9) vessel; 10) thermometer; 11) thermostat; 12)
manometer; 13) electric motor; 14) stopcock; 15) electric
timer; 16) calibrated orifice; 17) trap with liquid nitro-
gen; 18) volume meter.

Experimental Method

As follows from Eq. (1), in order to evaluate the burning-velocity constant, it is necessary to measure the burn-up velocity of the fuel drops. For this purpose the apparatus presented in Fig. 1 was employed. Air from a pump enters through electrical preheater 1 into pipe 2 with an internal diameter of 45 mm and 12 apertures, in any one of which centrifugal fuel jet 3 could have been installed. Interchangeable

atomizers with a small atomization cone are employed in the jet, as a result of which the amount of precipitation of fuel on the walls of the pipe remains insignificant. The temperature of the air at the inlet into the combustion chamber is determined with the aid of mercury thermometer 4. The fuel from the tank enters under pressure of nitrogen. The pressure is set on a manometer and determines the fuel flow rate. Combustion chamber 6 of rectangular cross section has quartz side walls in the initial portion.

The open end of the combustion chamber was in contact with the atmosphere. The slanting "two dimensional" flame tongue of atomized fuel was stabilized with the aid of one of two hydrogen burners 7 on the wall at the inlet into the combustion chamber. Moreover, the following were determined:

1) The CO_2, CO, and O_2 content in the exhaust combustion products along the height of the chamber in one particular section located at a certain distance from the inlet—by gas analysis of samples selected through cooled gas sampler 8;

2) The flow rate of the fuel and air and the extent of preliminary vaporization of the fuel. A special method (parts 9-16) was developed for recording the extent of vaporization.

The essence of this method consists in sampling and evaluating the composition of the gaseous phase of the fuel-air mixture; the composition was analyzed by the so-called thermodynamic method [9];

3) The local mixture compositions α ahead of the flame front—by measuring the amounts of fuel deposited in traps 17, which were cooled with liquid nitrogen, while a known amount of the fuel-air mixture was suctioned off through volume meter 18;

4) The distribution of the fuel drops according to dimensions in the flow at the inlet into the combustion chamber—from the imprints in the flow on rods coated with a layer of soot and magnesium oxide.

5) The trajectories of the drops in the burning zone—from photographs (Fig. 2);
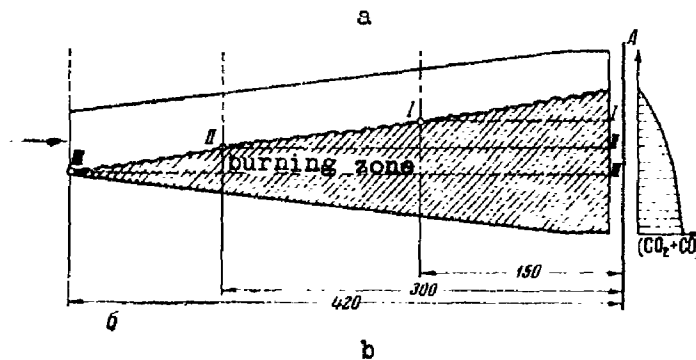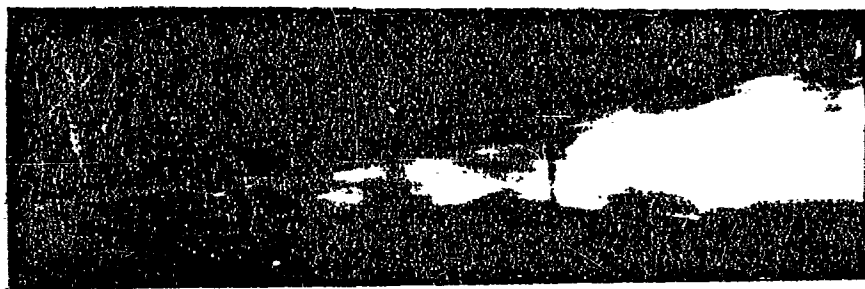
a

b

Fig. 2. a) photograph of the flame tongue;
b) diagram of this flame tongue with the
trajectories I—I; II—II; and III—III
A) section in which analysis of the gases
was carried out.

6) The flight velocity of the drops along three chosen trajectories—by photo-scanning the flame through a slit or film with a simultaneous time record.

In determining the complete combustion time of homogeneous mixtures τ_{hc} the flame was stabilized b, both hydrogen burners so as to create a "two dimensional" flame tongue symmetrical with respect to the axis; evaluated were: the average gas velocity in the flame tongue $\underline{v}$ by photoscanning the tracks of luminous magnesium particles which had been previously introduced into the flow through a slit located on the flow axis; the length of the burning zone δ ——— from the composition of the exhaust gases and by photographing the zone of luminescence. From which τ_{hc} = = δ/v.

Paraffin kerosene with a specific gravity of 0.82 g/cm^3 and a boiling range of 140-300°C served as the fuel. Elementary composition: carbon 85.7% hydrogen 14.0%, sundry impurities 0.3%. In certain experiments with homogeneous mixtures municipal gas containing up to 75% methane was used.

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Experimental Results

1. Burning-Velocity Constant of the Drops

In the determination of the velocity constant $\underline{k}$, firstly, Eq. (1) was assumed to be valid and, secondly, the mass exchange between trajectories was not taken into account as a result of which the values for $\underline{k}$ will be overstated on trajectories with a low degree of burn-up and understated on those with a high degree of burn-up.

It should be noted that the small combustion times ($\tau \leq 23$ m sec) justify this assumption to some extent.

From the distribution of the drop dimensions, which directly gives the information concerning the number of drops n_i in $\underline{i}$ groups of drops of given initial diameter D_o dimensionless curves of the burn-up η or completeness of combustion for different values of the product $k\tau$ were plotted (Fig. 3):

$$\eta = \frac{\Sigma n_i D_{0i}^3 - \Sigma n_i D_i^3}{\Sigma n_i D_{0i}^3} \, , \quad D_i = \sqrt{D_{0i}^2 - k\tau} \, . \tag{2}$$

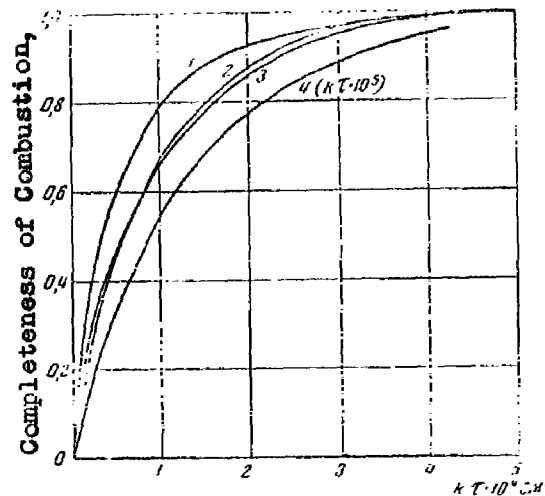
Fig. 3. Burn-up η as a function of $k\tau$. D_{av} equals: 88μ (1); 110μ (2); 108μ (3); 45μ (4)

The actual values of η were determined from the ratio

$$\eta = \frac{[CO_2 + CO]}{[CO_2 + CO]_{max}} \, . \tag{3}$$

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where $[CO_2 + CO]$ is the total percentage content according to the analysis of the gases; $[CO_2 + CO]_{max}$ is the maximum possible content of these gases from stoichiometric calculation for the local values of α.

From the values of η, the calculated value according to Eq. (2) and the actual value according to (3), the value of the product $k\tau$ can be obtained graphically. Finally, from the known trajectory length and flight velocity of the drops the combustion time τ and the value of the burning velocity constant are determined

$$k = \frac{k\tau}{\tau}.$$ (4)

Experiments were carried out for a practically negligible degree of preliminary vaporization along three trajectories: I-I, 150; II-II, 300; and III-III, 420 mm for different atomizers, centrifugal and pheumatic, giving a different fineness of atomization (average diameter of drops D_{av}) and macrodistribution. The total excess-air coefficient α was equal to 1; the temperature of the air at the input into the combustion chamber was 20-25°; the distance from the jet to the combustion chamber was 450 mm; and the air flow rate was 220 and 440 kg/hr, which corresponds to an average flow velocity $v = 35$ and 65 m/sec. The open end of the combustion chamber was in contact with the atmosphere. The results of the experiment are presented in Table 1.

TABLE 1

Determination of Burning-Velocity Constant

Type of atomizer D_{av}, μ	Trajectory	η	τ, msec	$k\tau$	k, cm²/sec	Average k, cm²/sec
			$v = 33$ m/sec			
Centrifugal 88	I — I	2,0	4,5	0,45	0,0056	
	II — II	0,78	10,5	0,66	0,0052	
	III — III	0,72	17,2	0,81	0,0058	
Centrifugal 108	I — I	0,55	4,3	0,34	0,0061	
	II — II	1,60	11,1	0,55	0,0059	0,0059
	III — III	0,83	20,0	0,71	0,0064	
Pneumatic 110	I — I	2,15	5,2	0,35	0,0058	
	II — II	1,25	12,5	0,55	0,0058	
	III — III	1,44	25,0	0,79	0,0066	
			$v = 65$ m/sec			
Centrifugal 45	I — I	1,04	2,5	0,27	0,002	
	II — II	0,85	5,4	0,78	0,0038	0,0000
	III — III	0,83	12,1	0,96	0,0033	

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As can be seen from Table 1, the burning-velocity constants of the drops $\underline{k}$ for $D_{av} = 88$—110μ and $v = 33$ m/sec lie within the limits 0.0052—0.0066 cm^2/sec; the average value out of ten measurements is 0.0059 cm^2/sec.

For $D_{av} = 45\mu$ and $v = 65$ m/sec the valuesof $\underline{k}$ are essentially equal: limits of 0.002—0.0038 and an average of 0.0030 cm^2/sec.
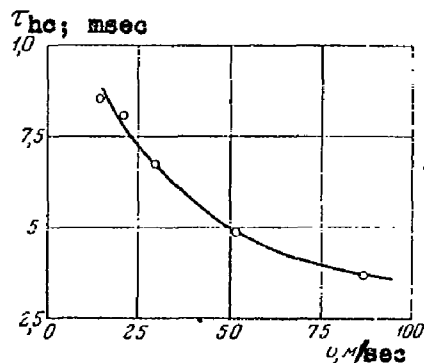

Fig. 4. Burning time τ_{hc} of homogeneous mixtures at different flow velocities $\underline{v}$

2. Burning Time of Homogeneous Mixtures

For a comparison of the time of total combustion of atomized fuel and homogeneous mixtures experiments were conducted to determine this time for stoichiometric compositions. The results of the measurements are presented in Fig. 4.

Discussion of Results

The results of the experiments do not permit us to judge the extent to which Eq. (1) is justified. This follows from an analysis of the accuracy of the individual measurements. In particular, on account of the steep rise in the concentration $[CO_2 + CO]$ along the height of the section (different τ), an accuracy of the order of 2-3 mm would have been required for the determination of the position of the trajectories along the height of the section, in order to determine the exponent of D with an accuracy to 1. Such an accuracy could not be achieved.

The values obtained for the constant $\underline{k}$, which characterize the absolute burning velocity of fuel drops in a turbulent flow, allow us to make a comparison with the numerous measurements that have been made under model idealized conditions. Some of these measurements have been collected in Table 2.

As can be seen, the value of $\underline{k}$ measured in our experiments for $D_{av} = 88$—110μ is 1.5 to 2 times lower than the values obtained for a single drop, but it coincides with the data of corresponding experiments with groups of drops of small [5], as well

as large dimensions (when the distance between them is small) [6, 8]. The theoretical conclusion that the turbulence of the medium and of the burning zone itself cannot appreciably change the vaporization rate of fuel drops when $D \leq 100\mu$ is, on the whole, confirmed.
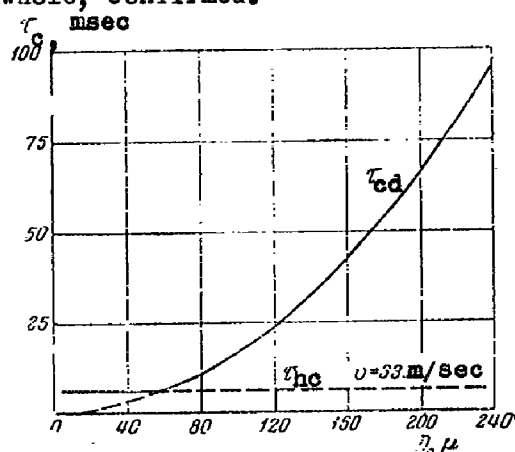

Fig. 5. Combustion time τ_{cd} of fuel drops of different diameters D_O

The complete combustion time τ of drops of different dimension according to Eq. (1) for $k = 0.0059$ cm^2/sec is presented in Fig. 5. For a diffusion mechanism the rate of combustion is determined by the rate of drop vaporization. As can be seen, for sufficiently fine drops the combustion time is commensurate with the burning time of a homogeneous mixture in a turbulent flame tongue τ_{hc} (Fig. 4) and

may even be less. Hence it follows that in a turbulent flow the rate of vaporization of these drops may exceed the rate of combustion of the vapor. For a flow velocity $v = 33$ m/sec and $D_{av} = 88$—110μ the condition $\tau_{cd} \leq \tau_{hc}$ arises as soon as $D_O \lesssim 60\mu$. The data in Table 1 for $v = 33$ m/sec refer to those degrees of fineness of atomization, for which the content of drops $D_O \leq 60\mu$ corresponded to 29% ($D_{av} = 88\mu$), 18% ($D_{av} = 108\mu$), and 12% $D_{av} = 110\mu$), i.e., generally small. It is therefore possible to assume that the values obtained for $\underline{k}$ refer to a diffusion combustion region, when the combustion rate can be neglected, and the limiting stage is the fuel vaporization. It was for this very case that the relationship (1) which we have used was obtained.

In experiments with $D_{av} = 45$, when $v = 65$ m/sec, the relationship $\tau_{cd} \leq \tau_{hc}$ arises as soon as $D_c \leq 50\mu$. In this case already more than half the drops (57% by weight) have a dimension $\leq 50\mu$, which apparently led to a significant understatement of the values obtained for $\underline{k}$. For these drops the vaporization rate is higher than

the vapor combustion rate, which indicates a transition from the diffusion region to a region governed by the law of turbulent gas combustion, i.e., the laws of kinetics and turbulence.

It should be noted here that since the burning zone around the drops is turbulent, it is necessary to estimate this transition in accordance with the combustion time of a homogeneous mixture in a turbulent flame, and not on the basis of purely kinetic data, as some authors have done, e.g., in Refs. [10, 11].

Thus the determination of $\underline{k}$ permits us not only to estimate the burning velocity, but, when the value of τ_{hc} is known, to establish the critical drop diameters, above and below which significantly different combustion laws come into effect.

The purpose of this paper was to evaluate the burning-velocity constant $\underline{k}$ in a turbulent flow, in order to compare it with its values in experiments with single drops, as well as to compare the combustion times of drops and homogeneous mixtures for a determination of the value of the critical drop diameter under the conditions of the given experiment.

Note that knowledge of the critical drop diameter is useful under any concrete technical conditions of burning, since it permits us to judge the effect that a change in the drop dimensions has on burning. Let us consider this in the case of a diesel engine. Here in the presence of coarse atomization, when the drop diameter is many times greater than the critical diameter, we can expect slow burning. On the other hand, if the drop diameter is less than critical, reduction of the combustion time by further reduction of the drop diameter is impossible.

With the aid of the data obtained it is possible to make a purely approximate estimate of this critical dimension. For this purpose, it is necessary, above all, to know the combustion-rate constant $\underline{k}$ corresponding to the conditions in a diesel engine. Using the value we have obtained for $\underline{k}$, we shall introduce a correction for high air pressures and temperatures. The value of $\underline{k}$ in stationary air for a single drop increases with an increase in pressure from 1 to 20 atm in proportion to a power of 0.25 [2].

TABLE 2

Experimental Values of Combustion-Rate Constants

k, cm^2/sec	D_c, μ	State of medium	Other conditions	author
		Experimental conditions		
Diesel fuel				
0,0076	... 2400	Stationary		[1]
Kerosene				
~0,06	1500—2500	Stationary		[1]
0,035—0,04 *	200—400	"	$T = 710°$, flight of a single drop	[2]
Benzene		Stationary		
0,0097	1500—...60	"		[1]
0,0099	1500—1800	"		[3]
0,012—0,013	1500—1800	"		[3]
0,0135	1500—1800	Blast ... 5,4 ... sec		[3]
~0,090—0,0137	1500—1800	Stationary	$T = 710—800°$,	[4]
...0,03	90	"	flight of a group of drops	[5]
Toluene		Stationary		
0,0066	1500—2000	"		[1]
0,0077	1500—1800			[3]
Isooctane		Stationary		
0,0095	1500—1800	n-heptane		[1]
n-heptane		Stationary		
0,0097	1500—2000	"		[1]
0,0084	1500—1800	"		[3]
0,011—0,015	1500—1800	Blast	$T = 135°$	[3]
0,0114	1500—1800	$v = 39,4$ см/sec		[3]
0,007—0,0157	1180—2090	Stationary	2 drops, distance 300—1470 μ	[6]
0,012—0,015	—	Stationary	$T = 700—800°$	[4]
0,005	—	"		[7]
0,010	—	Accel. of the drop.		[7]
0,0127	—	Stationary	9 drops, distance 9,5 . .	[8]
0,0077	—	"	9 drops, distance 3,6 ...	[8]
0,0047	90	"		[5]
Cyclohexane				
0,0066	90	Stationary		[5]
Propanol				
0,0046	90	Stationary		[5]
Ethyl alcohol				
0,0104	—	Stationary	9 drops, distance 5,6 мм	[8]
0,00637	—	"	9 drops, distance 3,6 мм	[8]
0,0081	1500—2000	"		[1]
0,0086		"		[2]
0,0107		Blast $v = 39,4$ см/sec		[2]
0,0053—0,0091	1180—2090	Stationary	2 drops, distance	[6]

* Read from graphs

The value of $\underline{k}$ also increases with increase in air temperature, although apparently less rapidly. Thus, according to the experiments, for large single drops of diesel fuel at room temperature $k = 0.0079$ cm^2/sec[1],while at $600°C$ $k = \sim 0.01$ cm^2/sec [4]. Since the temperature correction is apparently slight, we shall not introduce it into our approximate calculation.

Taking the value of the compression pressure in a diesel engine to be p = 30 atm and extrapolating the function obtained in [2] to this pressure, we find the value

$$k = 0,0059 \left(\frac{30}{1}\right)^{0.25} = 0,0138 \ c.u^2/sec$$

On the other hand, it is necessary to determine the combustion time of a nearly stoichiometric homogeneous mixture. This was done with the aid of data at our disposal and was partially published in [12].

It is permissible to estimate τ_{hc} as the time of fast pressure rise during combustion according to the indicator diagrams corresponding to the process of self-ignition of homogeneous mixtures as a result of compression. In this case for hydrocarbon-air mixtures (for diesel type fuels) under conditions of high temperatures and pressures the values obtained for τ_{cd} are of the order of 0.5—1 m sec. It is possible to estimate τ_{hc} from schlieren movie recordings as the time during which the gas remains in the flame front, while the flame propagates from a spark in homogeneous mixtures $\tau_{hc} = \dfrac{\delta}{u_T}$ where u_T is the propagation velocity of the flame, and δ is the width of the combustion zone. In this case values of τ_{hc} of the order of 1-2 msec are obtained. On the average, τ_{hc} may be taken equal to 1 msec = 10^{-3} sec. By definition $\tau_{cd} = \tau_{hc}$ for the critical drop diameter, so that we obtain

$$D_{cr} = \sqrt{k\tau_{hc}} = \sqrt{0,0138 \cdot 10^{-3}} = 0,0037 \, cm \approx 40 \, \mu.$$

If the estimate has been made more or less correctly, this means that an appreciable **reduction** of the combustion time for short ignition delays (during the course of which the dimensions of large drops remain almost unchanged) by decreasing the drop diameter below 40μ is practically impossible. Since the conditions in our experiments on the determination of the values of $\underline{k}$ are extremely different from the

combustion conditions in a diesel engine, and since the influence of preliminary vaporization on the drop diameter was not taken into account, the calculation performed above is merely illustrative in nature.

Because it is important to have an idea of the possible means of controlling the combustion process, extensive investigations of the values of the burning-velocity constant and the burning time under different specific conditions of ignition of atomized fuel are required.

Conclusions

1. The value of the diffusion constant of the drop burning velocity has been obtained for the conditions of burning of atomized kerosene in a turbulent flow with an initial temperature of $20^{\circ}C$ at 1 atm: $k = 0.0059 \; cm^2/sec.$

2. The minimum critical drop diameter, which limits the diffusion combustion region under the given burning conditions, has been established.

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